A review of past and future seismometers on the Moon

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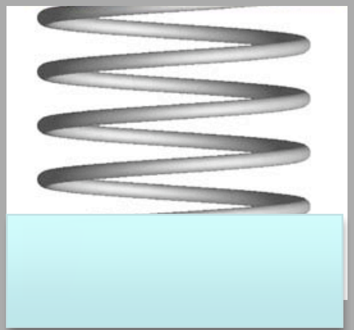
NLSI Lunar Science Conference, NASA Ames, July 2010

Summary

- What is a seismometer ?
- Why send a seismometer to the Moon ?
- Past seismometers on the Moon
- What have we learned ? What's left to learn ?
- Which requirements for the next seismometers ?
- The technical challenges of geophysical packages and seismometers
- Some Incoming Missions
- The LBBS – VBB instrument
- Performance sheet
- What's next ?

- It's basically a device converting the ground motion (position, speed or acceleration) into a signal that can be recorded
- Two options can be considered :
  - Monitoring of the motion of a proof mass (inertial reference)
  - Monitoring of the motion of a reference point versus another
- The ground motion is therefore converted first in mass motion, then the mass motion is converted into a signal to be recorded
  - And here come the problems
    - Linearity
    - Clipping (Trade-off between the amplitude of the mass motion and the resolution required for the signal)
    - Temperature variations

Q, ω_0



δx

Clipping

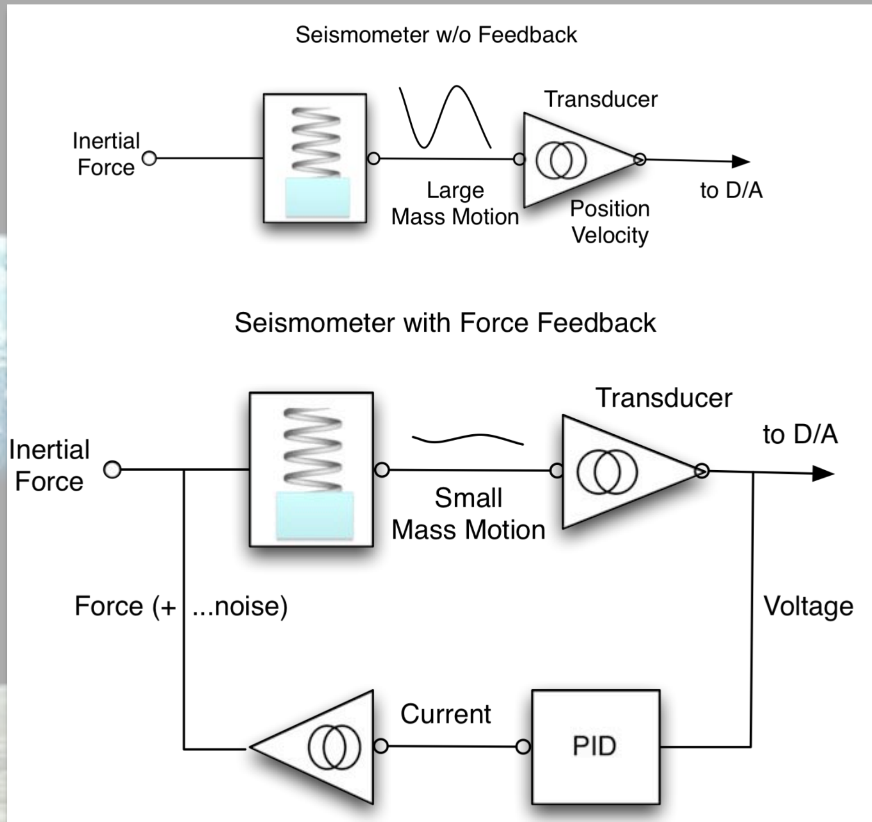
$$\underbrace{|\delta g|}_{\text{resolution in acceleration}} = \omega_0^2 \underbrace{|\delta x|}_{\text{resolution of the sensor}}$$

Brownian noise

$$a_b = \sqrt{\frac{4kT\omega_0}{mQ}}$$

(White noise PSD)

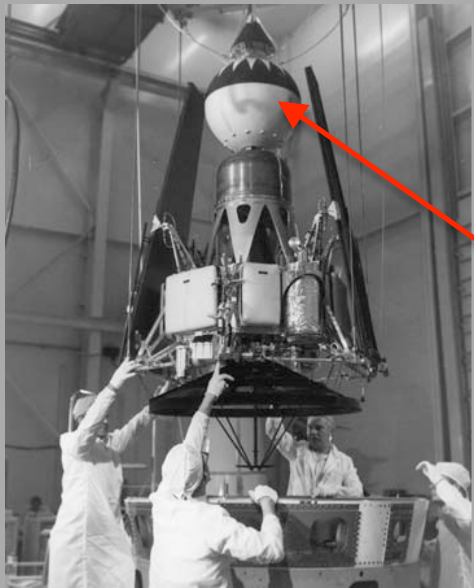
T is the temperature
Q is the quality factor of the resonator
ω_0 is the resonant frequency
m is the proof mass

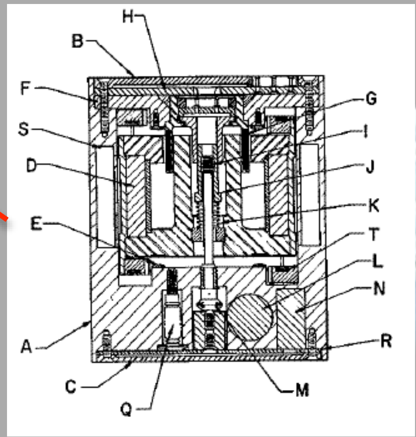


(From Wieland, 2004)

- A seismometer is just a (very) long period, very, very sensitive accelerometer. Most of the time analog …
- No « cool factor » …(e.g no laser shooting, no 3D image)
- However ..
  - Visible IR Imagers , Spectrometers : first microns
  - Neutrons : up to a meter
  - GPR : meters to km (best cases)
  - Seismometers : sounding down to the core
    - Two main techniques
      - Rays : profile of speed
      - Modes inversion
    - Additional Science : environment study
      - Presence of quakes for future settlement
      - Impact Science

Ranger Seismometer

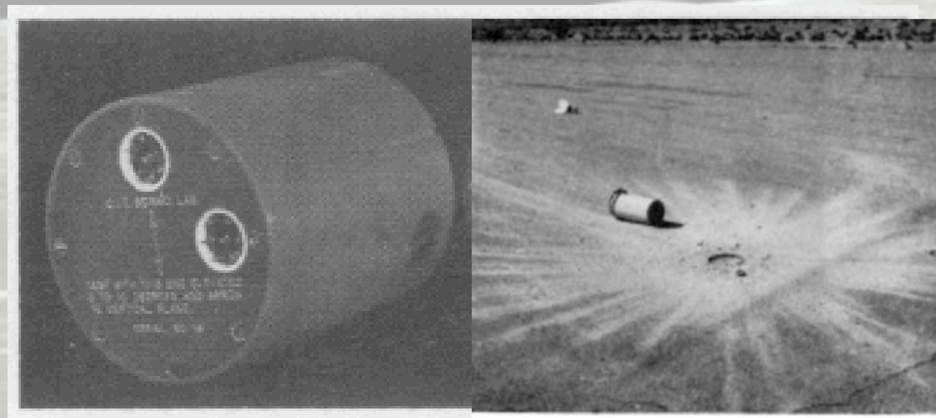




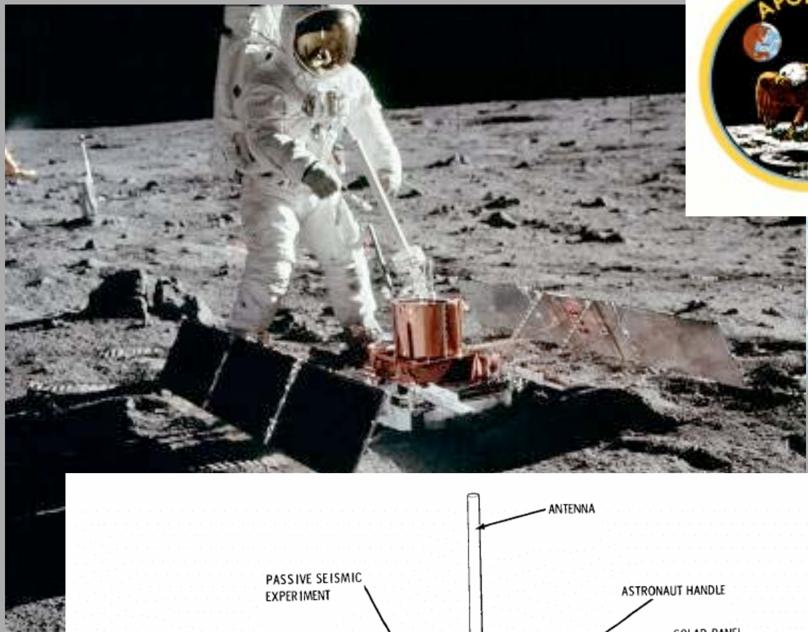
Lehner *et al. (1962)*

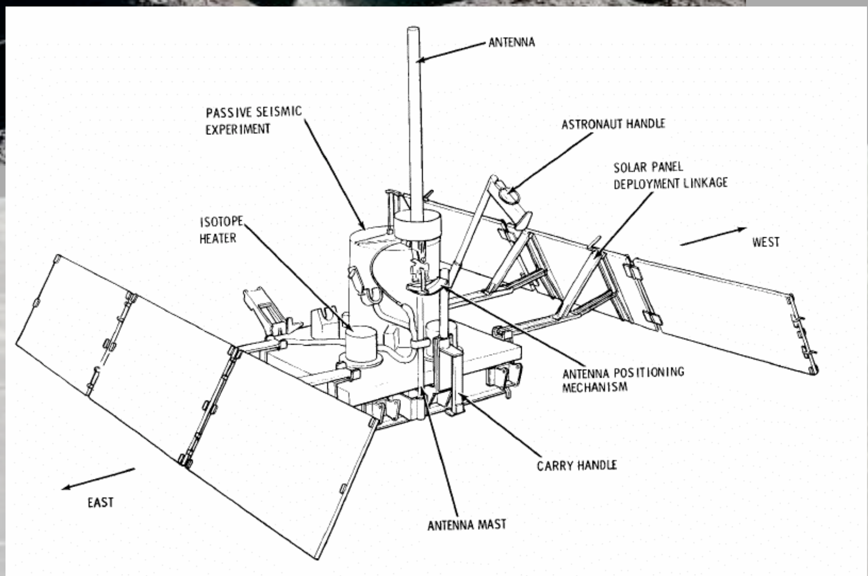
	Ranger
Bandwidth [Hz]	0.05-5
Natural period [sec]	1
Max amplification	1.7e+6 @ 4 Hz
Physical principle	Mass-spring
Details	Mass: magnet Spring: coil type Sensor: Velocity transducer
Weight [kg]	3.4
Dimensions [mm]	ϕ=111 L=133.4

- Mass – spring (geophone concept)
- Hard landing concept
- Liquid filled to block mass - drained in moon
- 30 days experiment
- Adaptation for earth testing (spring and adjustment screw changed)



Apollo 11





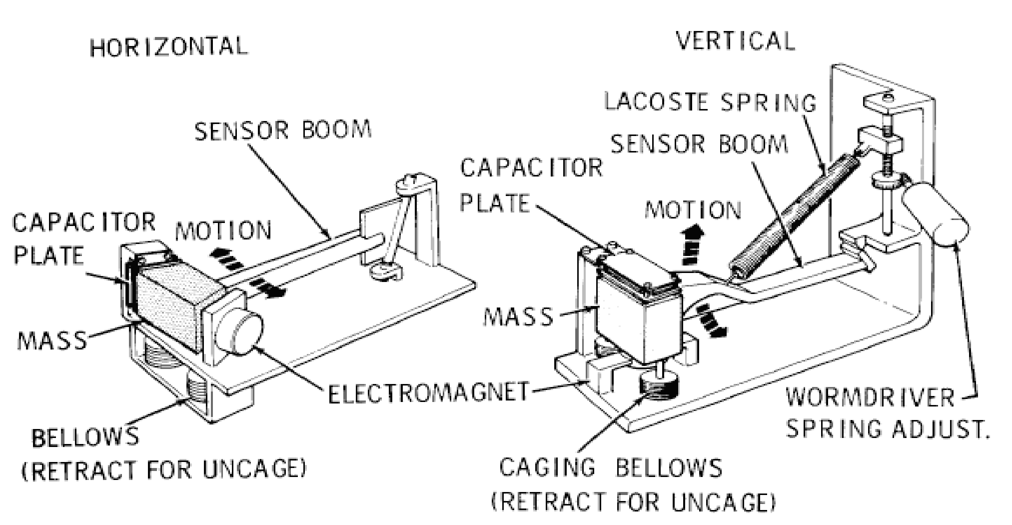
	Apollo 11 PSEP LP
Bandwidth [Hz]	0.004-1
Natural period [sec]	15
Max sensitivity	0.5e-10 m @ 0.45 Hz
Physical principle	Mass-spring
Details	Mass: pendulum Spring: springs, hinges, Lacoste springs Sensor: Movement transducer
Weight [kg]	48 (whole instrument)
Dimensions [mm]	ϕ=279 L=381 (container only)
Allowed Misalignment [deg]	ND
Works on Earth	ND
Levelling mechanism	Yes. Manual astronauts levelling system (+/- 5°). Gimballed system to level the sensor (+/- 2 arc sec)
Self Testing	Yes. Increment or step current in the coil
Power [W]	ND
Thermal Power [W]	ND
AFT [°C]	51.6 +/-10

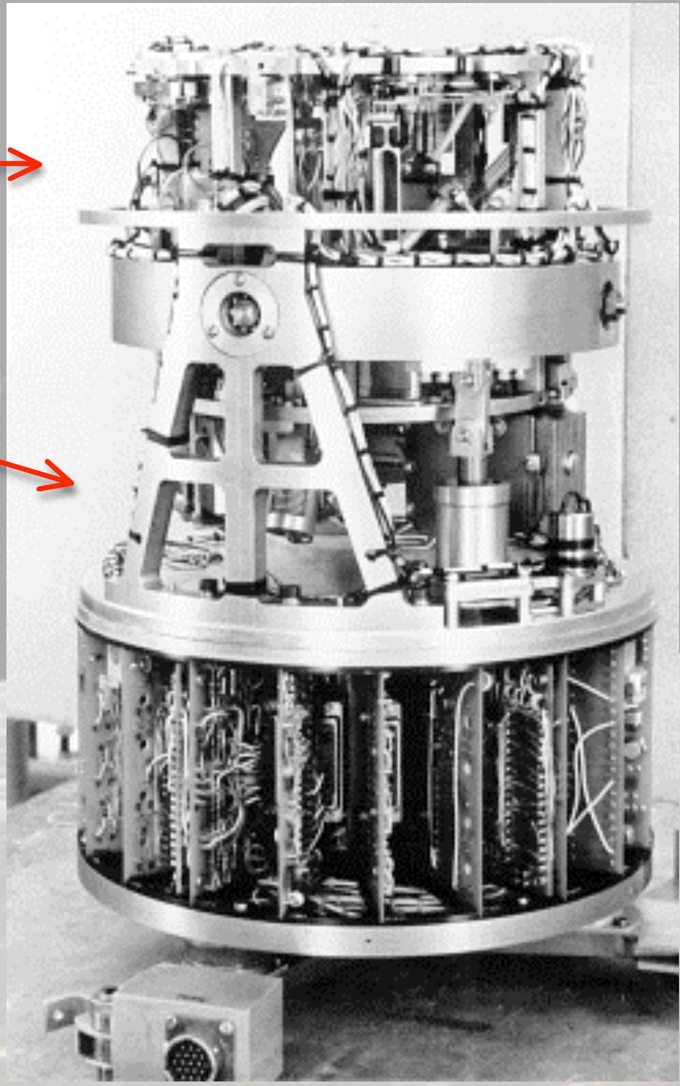
3 Long Period Seismometers

- Mass-spring (mass, levers, springs, Lacoste spring, hinges)
- Movement sensor
- Free period = 15 sec
- Bandwidth = 0.004-3 Hz

Short Period Seismometer (Velocity)

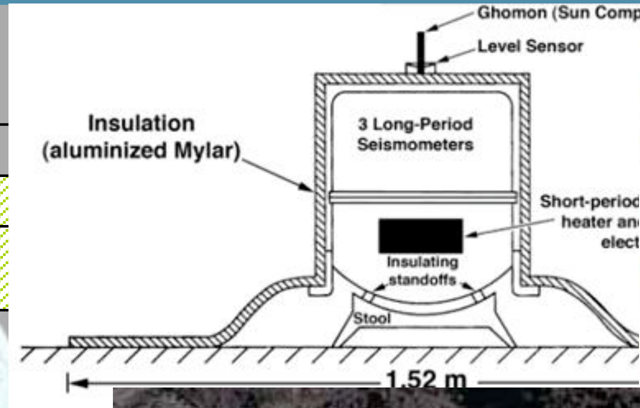
- Mass-spring (magnet-coil in a coil)
- Free period = 1 sec
- Bandwidth = 0.05-20 Hz

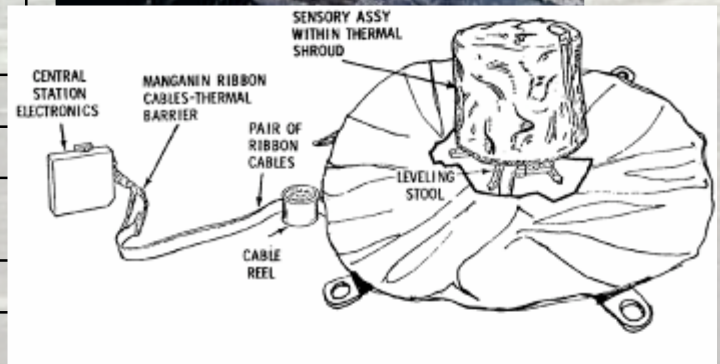




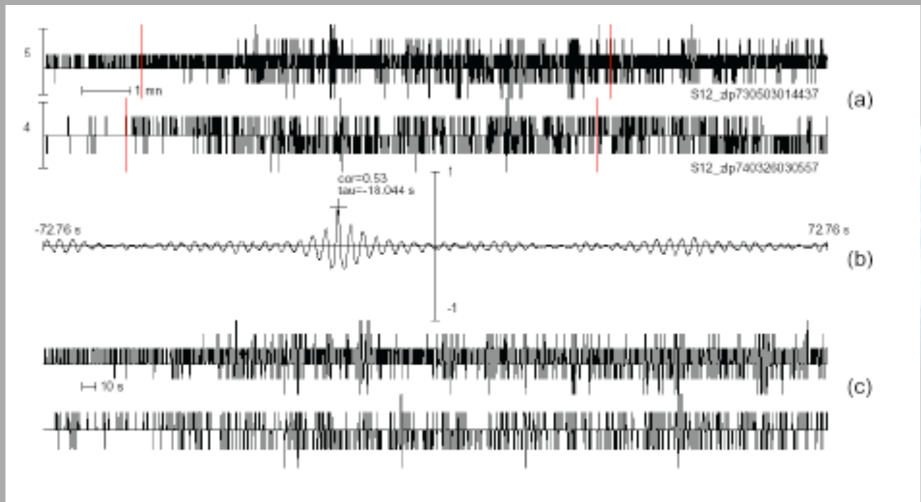
Apollo 12, 14-16

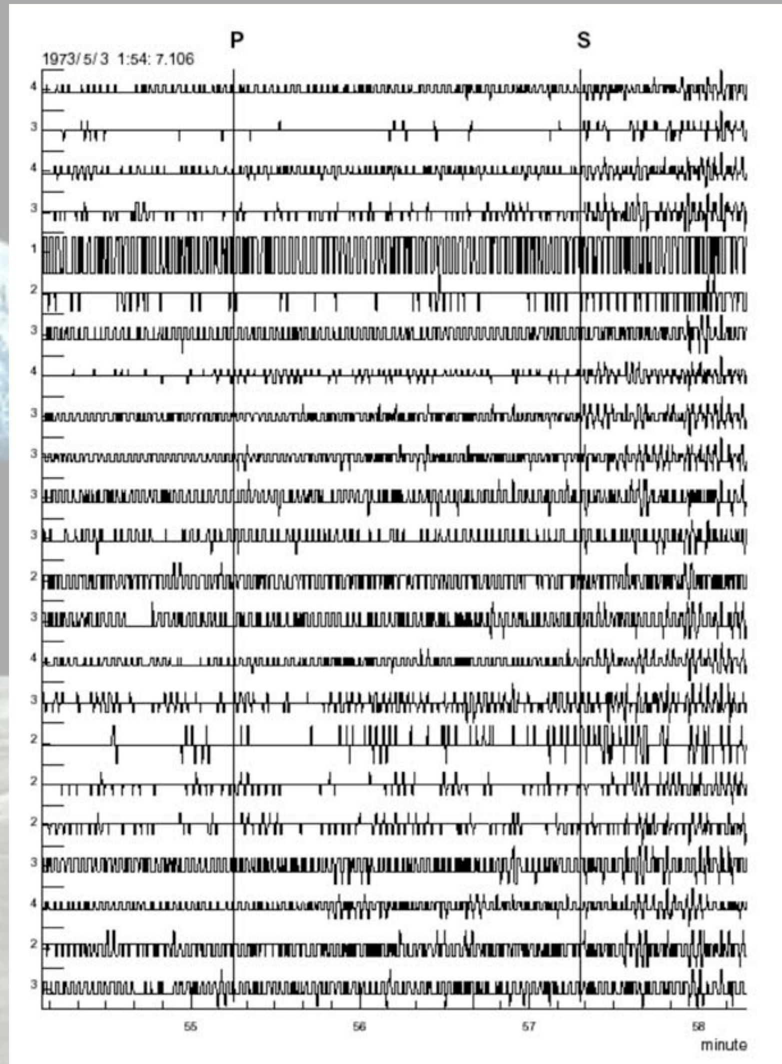
	Apollo 12-16 PSE LP	Apollo 12-16 PSE SP
Bandwidth [Hz]	0.004-2	0.05-20
Natural period [sec]	15 (by design) 2.2 (after op modif)	1
Max sensitivity	0.5e-10 m @ 0.45 Hz 3e-10 m @ 0.1-1 Hz	0.3e-9 m @ 1 Hz 0.5e-10 m @ 8 Hz 8e-4 cm/s2 @ 10 Hz
Physical principle	Mass-spring	Mass-spring
Details	Mass: pendulum Springs, hinges, Lacoste springs Sensor: Movement transducer	Mass: magnet Spring: coil type Sensor: Velocity transducer
Weight [kg]	11.5 (all sensors)	
Dimensions [mm]	ϕ=230 L=290 (container)	
Works on Earth	ND	ND
Levelling mechanism	Yes. Manual astronauts levelling system (+/- 5°). Gimballed system to level the sensor (+/- 2 arc sec)	
Self Testing	Yes. Increment or step current in the coil	
Power [W]	4.3-7.4	
Thermal Power [W]	2.5 (Apollo 12) 6 (Apollo 14-16)	
AFT [°C]	51.6 +/-10	





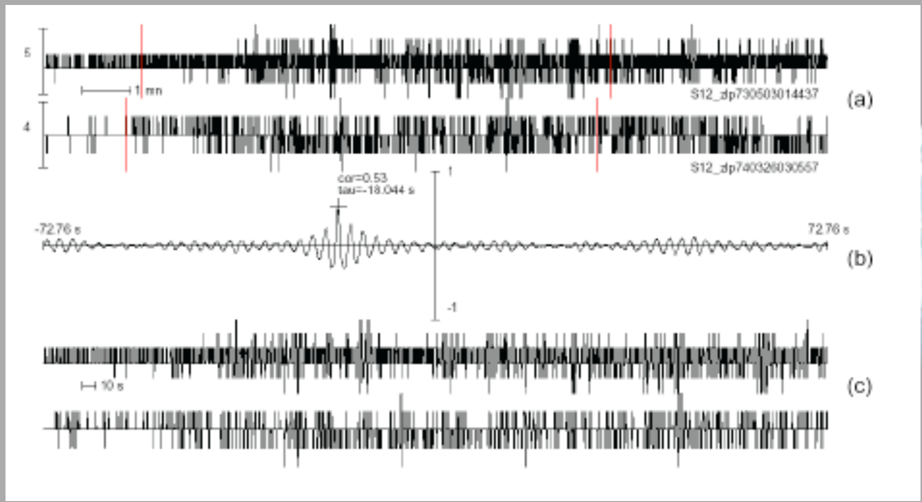
- Typical Apollo Data 12 bits

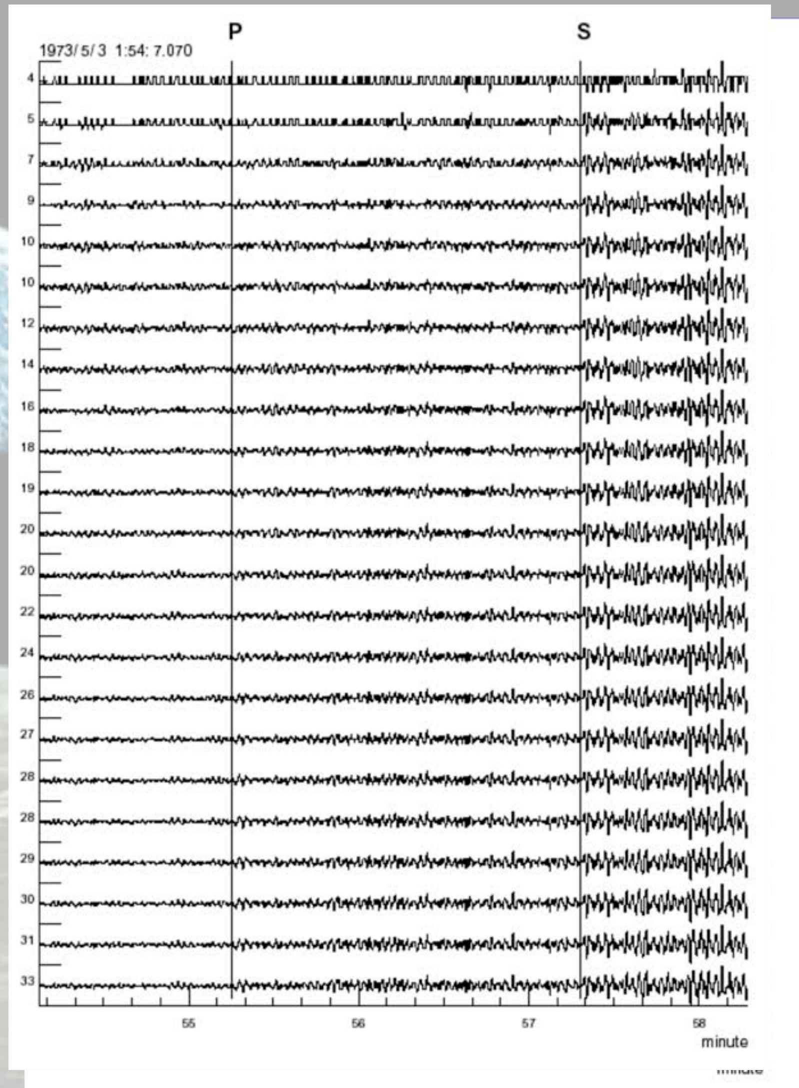




- Example of two quakes with the same deep focus and their cross-correlation
- Arrival time can be determined to allow staking

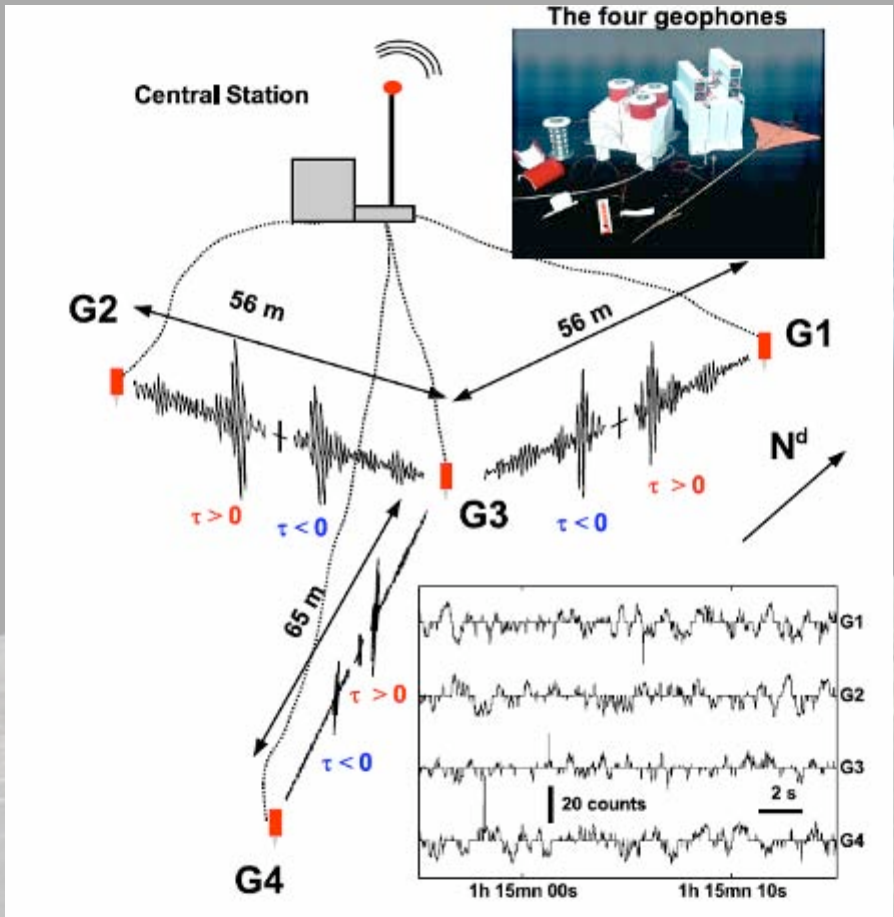
- Typical Apollo Data 12 bits





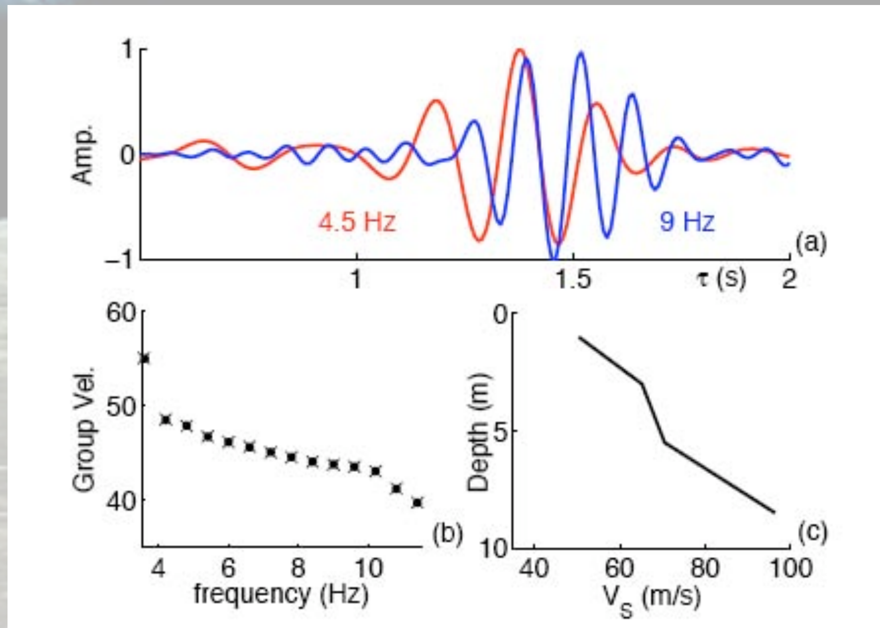
- Example of two quakes with the same deep focus and their cross-correlation
- Arrival time can be determined to allow staking

Apollo 17 experiment



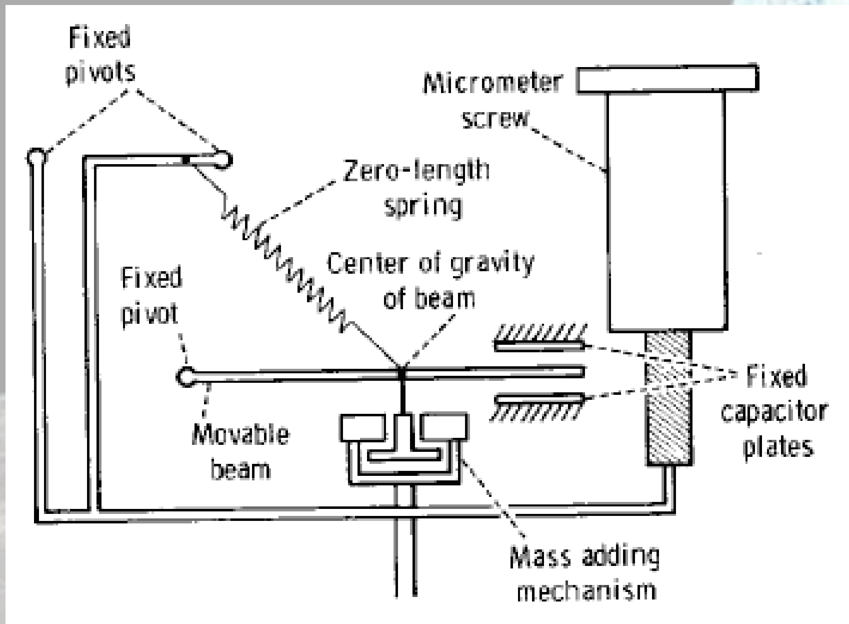
Larose, A Khan et all, 2003

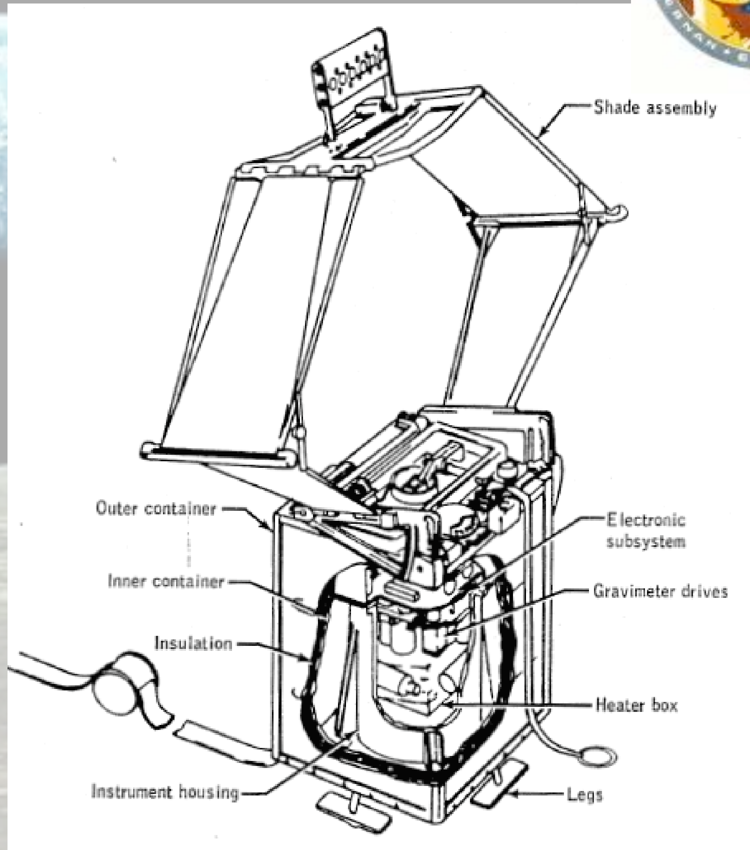
- 4 geophones
  - ✓ Base Length 60 m
  - ✓ Depth 10 m
  - ✓ Frequency 4,5 - 9Hz



1972 - Apollo 17

- Designed for gravitational waves detection
  (thanks to low seismic noise in the Moon)





- 3 containers, pressurized for lubrication and damping
- Bubble level at top (sunshield)
- Balance system w/micrometer screws to set pivot points
- Mass modification system (failed)

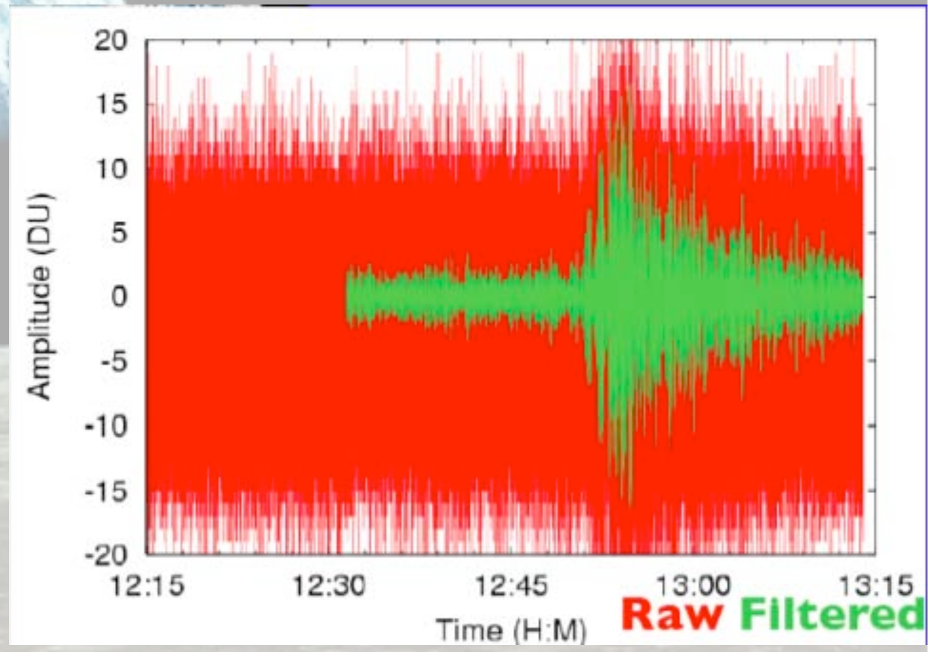
Results:

- used as a single-axis seismo
- "fourth ASN station"

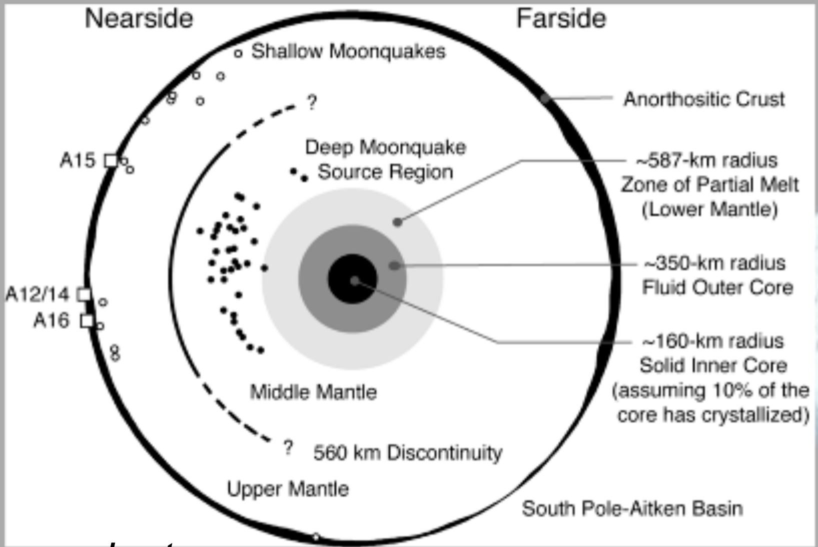
Interpreted 30 years after
allowed to analyzed 40/60 unallocated events and determine 5 of them (1 in the far side)

Also enhanced location error of
already analyzed events

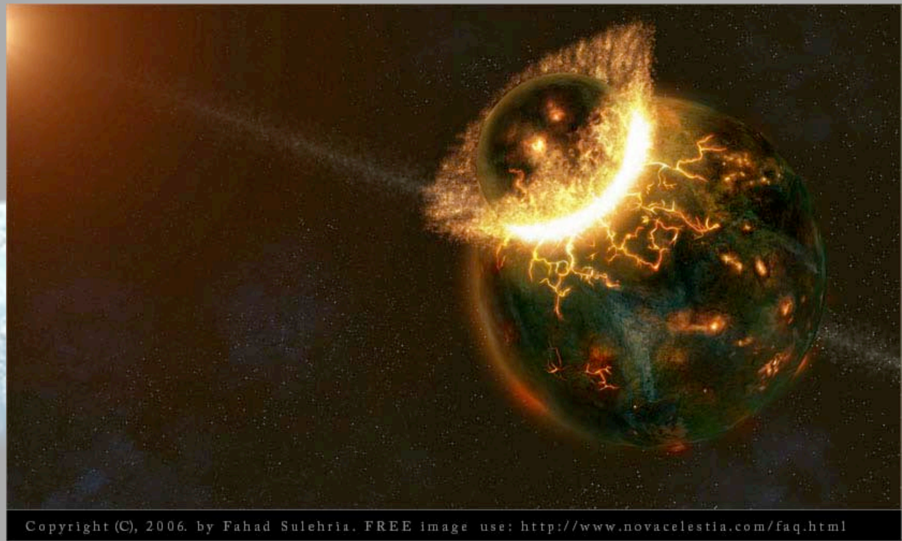
Kawamura et al, 2010

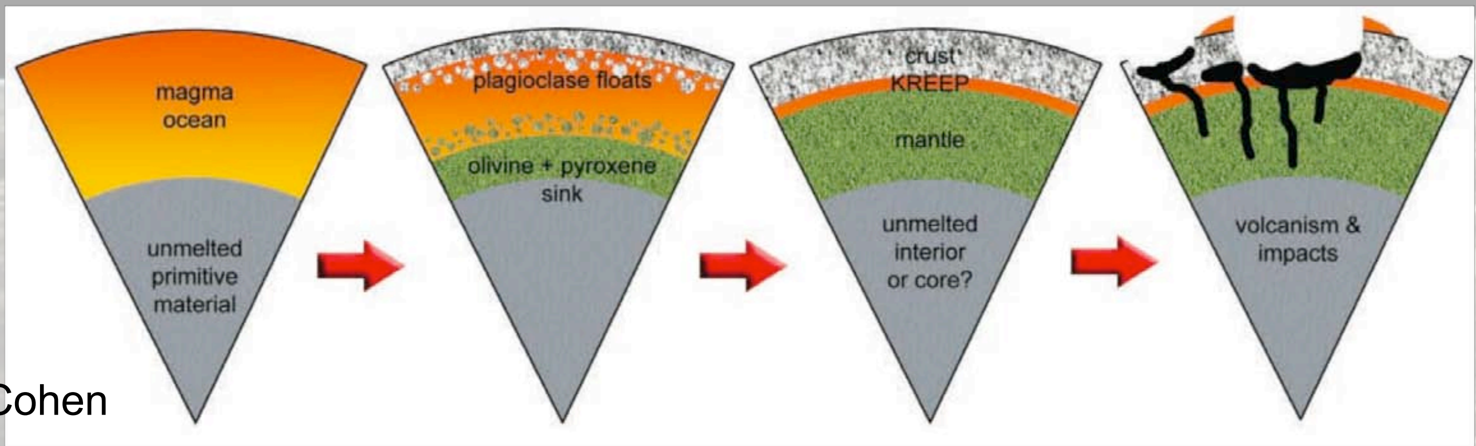


This is not LCROSS



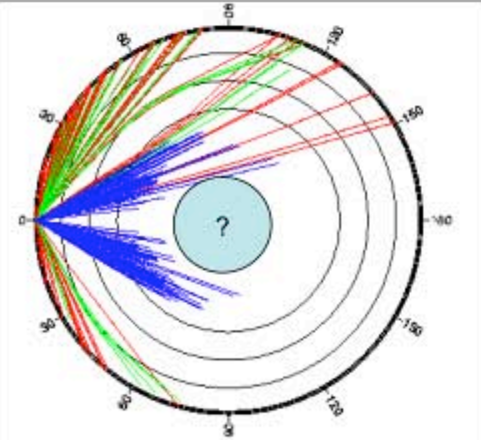
Wieczorek et al. 2006





NRC/B. Cohen

Existence and Size of the lunar core

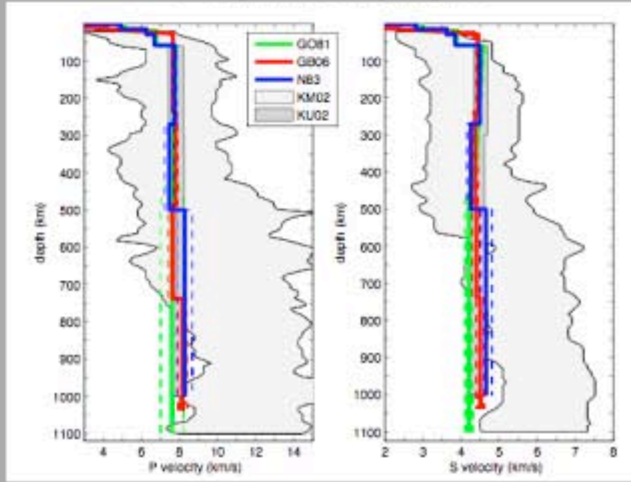


All ray paths available in the Moon. Blue is for deep events, red for impacts, green for superficial moonquakes

Size, composition of the core, former dynamo ?

From (Lognonné, 2007)

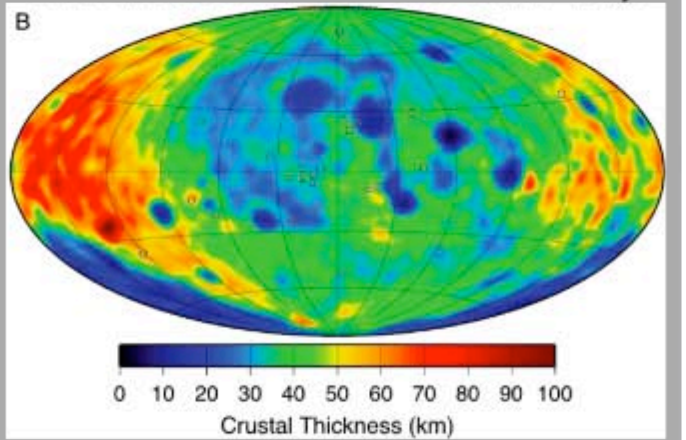
Refinement of P and S waves velocity profiles as a function of depth



Thickness of the crust (38, 45, 60 km ?)
Upper mantle discontinuities at 500 km ?
Constraints on Mineralogy

(Nakamura, 1983)
(Goins, Dainty and N.Toksöz, 1981)
(Lognonné, 2003, Gagnepain-Beyneix 2006)
(Khan et al, 2000)
(Khan and Mosegard, 2002)

Determination of the thickness of the lunar crust and characterize its lateral variability.



Consistency with gravity data, surface composition and heat flux needed

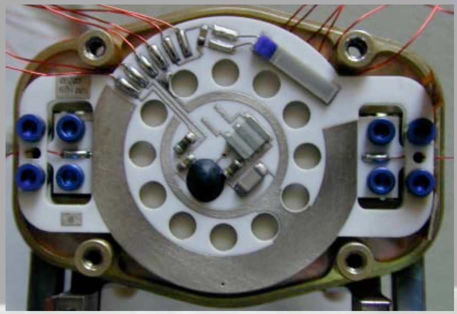
(Chenet et al, 2006)

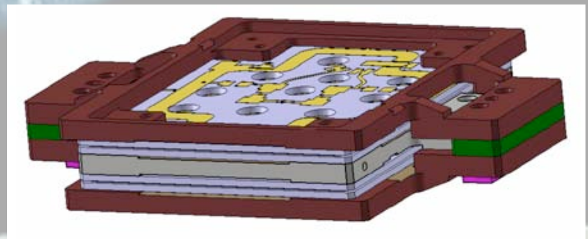
Science Objective	Traceability to SCEM report	Measurement Requirements	Mission Requirements	Instrument Requirements
1. Understand the current seismic state and determine the internal structure of the moon	2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales. 2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle. 2c. Determine the size, composition, and state (solid/liquid) of the core of the moon. 3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.	Measure lunar seismicity over the frequency range 1mHz–20Hz at multiple, geometrically dispersed locations.	4 simultaneously operating nodes Continuous operation for 1 lunar tidal cycle (6 years) Inter-station timing accuracy ~5 msec Instrument attached to ground; spacecraft vibrationally isolated from ground Thermally isolate ground to ~1 m radius	Three-axis Very Broad Band seismometers Dynamic range of ~ 24 bits For $1.0 < f < 20$ Hz, PSD $\leq 10^{-9} f^2$ m/s²/Hz$^{1/2}$ For $0.1 < f < 1.0$ Hz, PSD $\leq 10^{-10} f$ m/s²/Hz$^{1/2}$ For $0.001 < f < 0.1$ Hz, PSD $\leq 2\times10^{-11.5/f/2}$ m/s²/Hz$^{1/2}$

(From ILN Final Report)

- Sensitivity, resolution
  - A seismometer needs to be heavy (or very cold !) to be good $a_b = \sqrt{\frac{4kT\omega}{mQ}}$
  - Need of a very sensitive position transducer

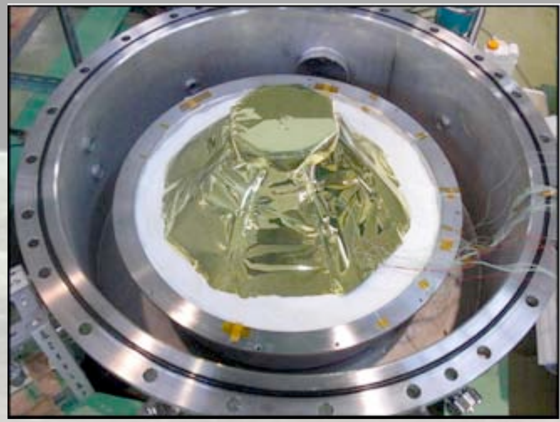
Seismometer Period (s)	10	5	2	0,5
Acceleration (m.s^-2)	1,00E-12	1,00E-12	1,00E-12	1,00E-12
Resolution (pm)	2,5E+00	6,3E-01	1,0E-01	6,3E-03





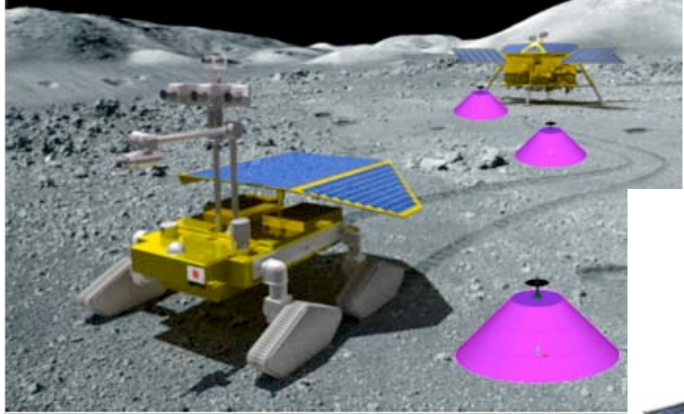
- Deployment
  - Coupling with the ground needed
  - Complex deployment scheme : human made or robotics
  - Need of additional mass

- Surviving the Lunar environment (= the lunar night)
  - Thermal environment
    - Apollo 11 seismometer stopped working from thermal problems
    - Problems solved with RPS
    - Next generation needs cautious thermal design
      - Use of a skirt to avoid the albedo during the day
      - Use of variable thermal conductances (louvers, thermal switches ….)
  - Radiation (15 krad)
- AIV : tests on Earth
- Long Life needed
  - Use of robust, proven technologies
  - Redundancy on critical subsystems

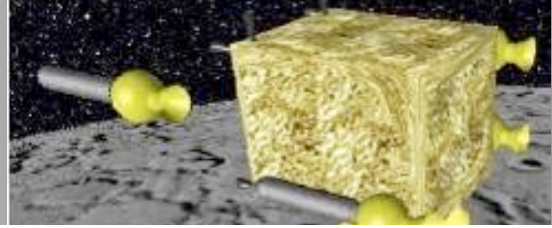


ISAS/JAXA

- He likes company (Mole, Laser Retroreflector …)

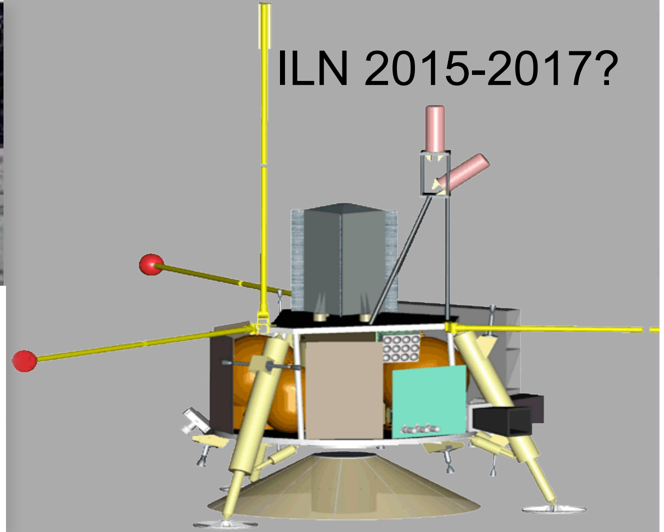


Selene-2 (JAXA) 2015



MoonLite 201X ?

Luna Glob 2012 ?



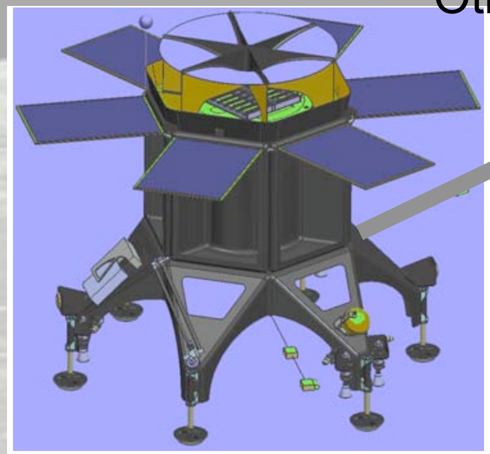
ILN 2015-2017?

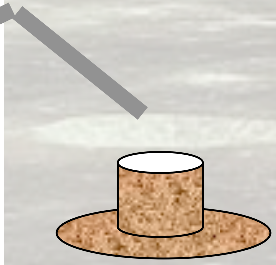
Chang'e 3 2013 ?

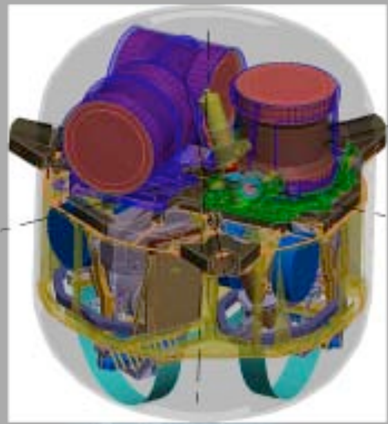
Artist rendering of Chang'e-3 lander and rover

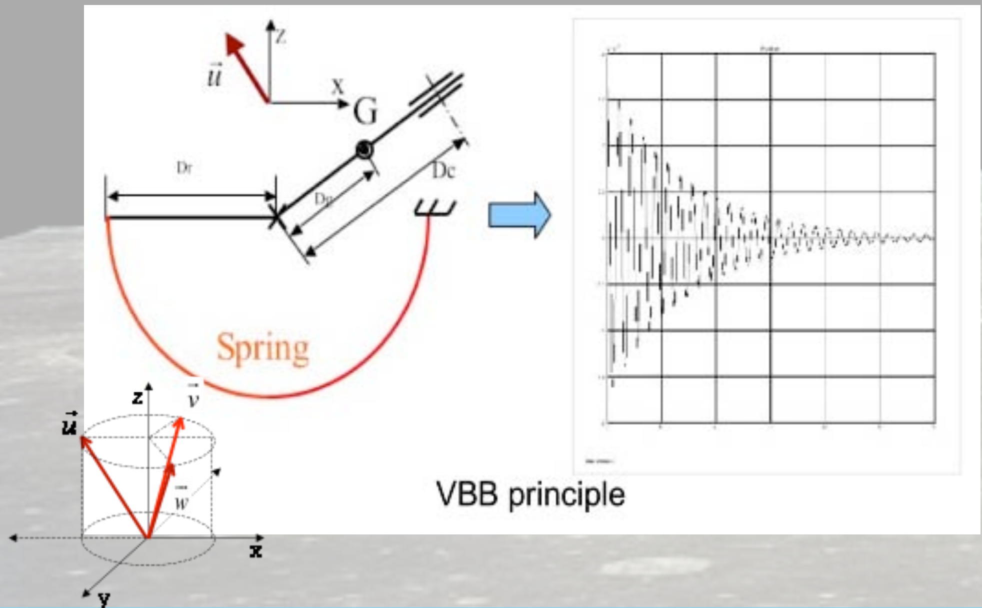
-China Academy of Space Technology

Other Proposals ?

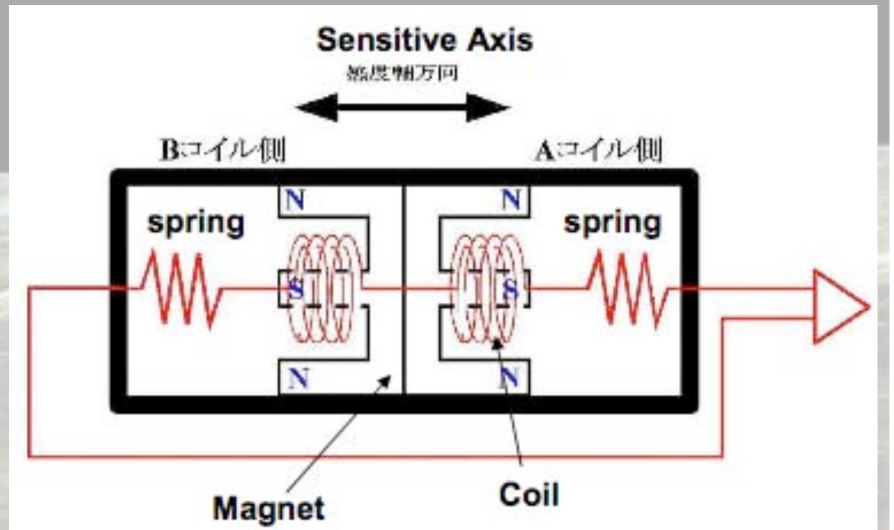


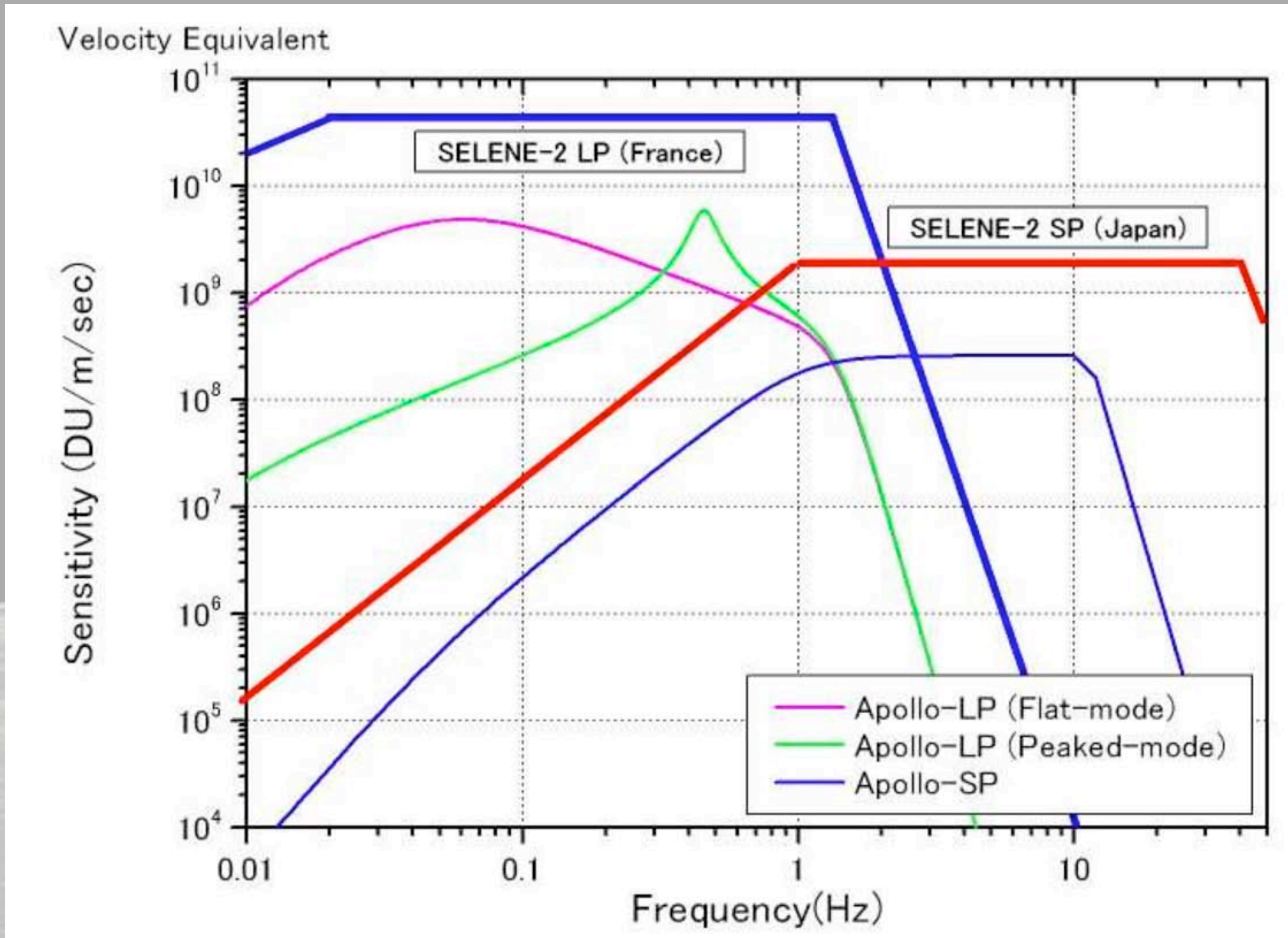


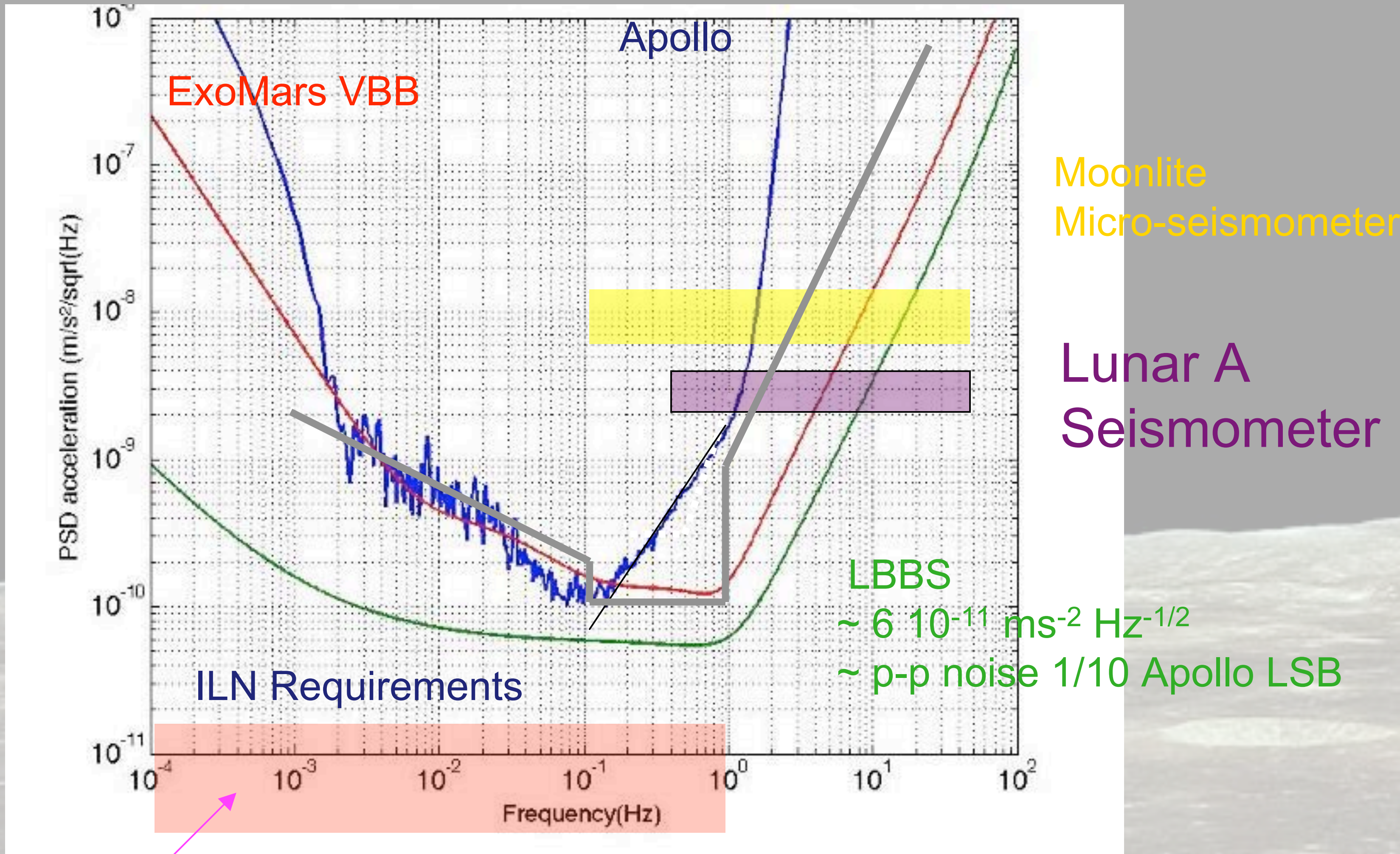




VBB principle



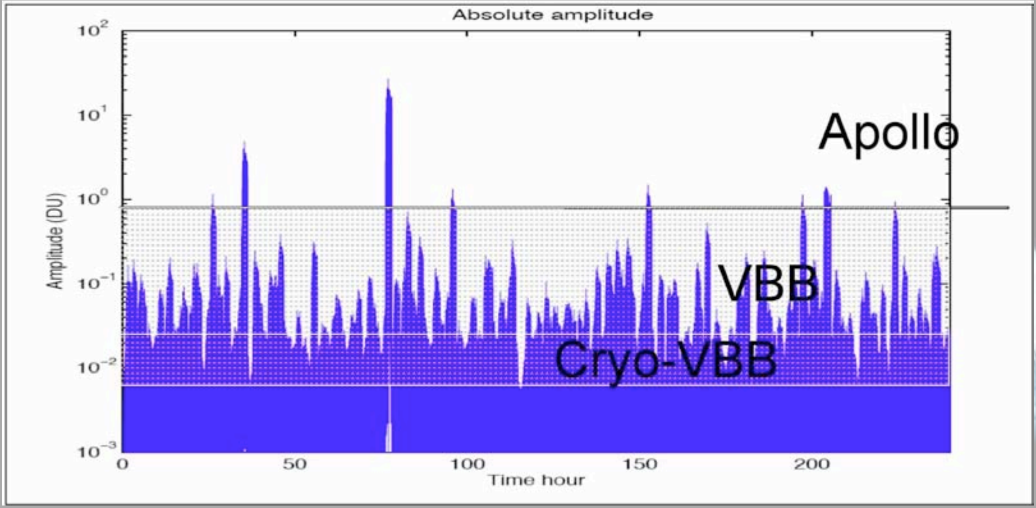

Velocity Equivalent
Sensitivity (DU/m/sec)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
SELENE-2 LP (France)
SELENE-2 SP (Japan)
Apollo-LP (Flat-mode)
Apollo-LP (Peaked-mode)
Apollo-SP
0.01
0.1
1
10
Frequency(Hz)



Superconducting gravimeters (SCG, to be developped)

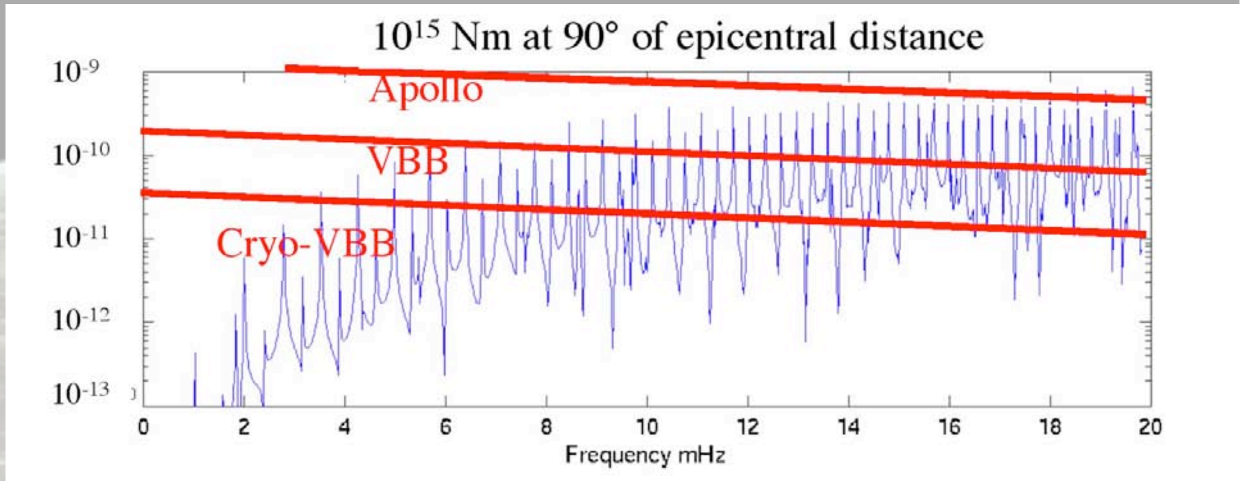
What's Next ?

Uhhh….first, let's fly a geophysics mission….



See the meteoritic hum ….
(Lognonné, 2009)

And low frequency modes …



Cryo VBB on ESA Moonnext ?
Laser Strainmeter ?
(cf Araya, 2003) ?

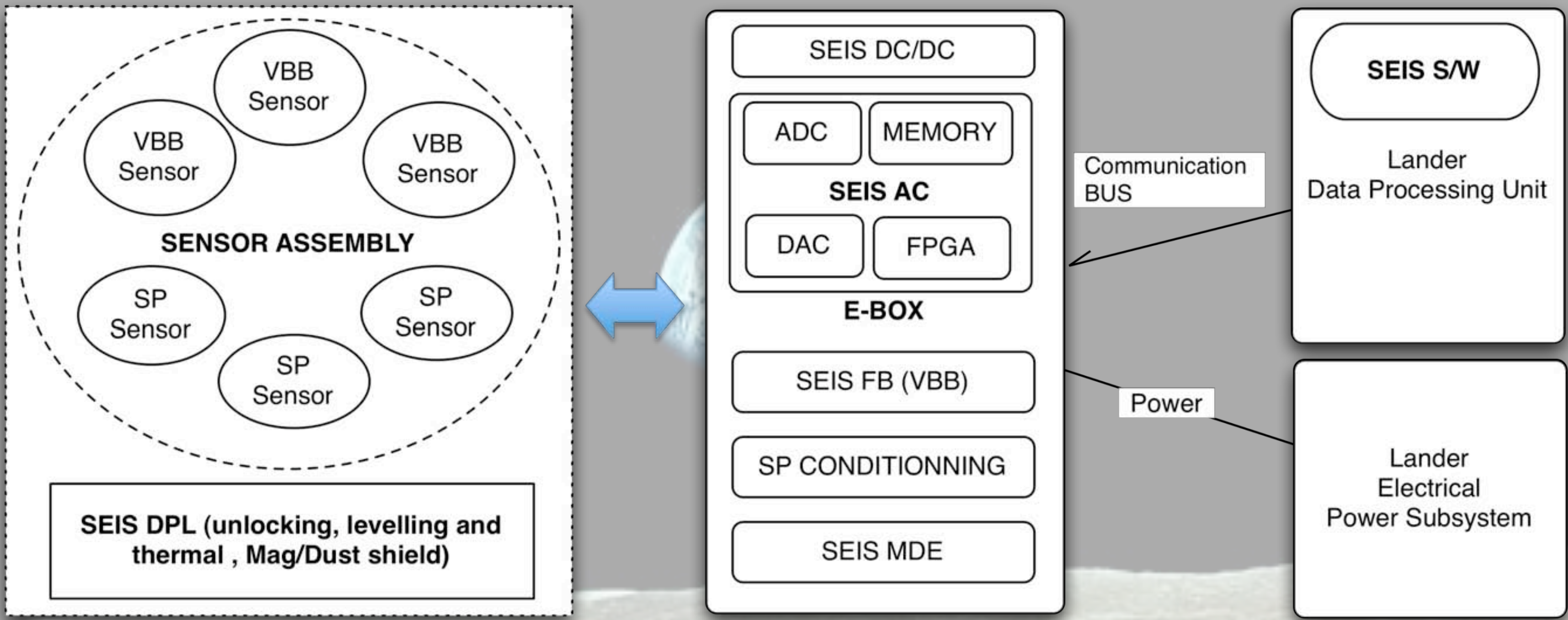
10^{15} Nm (!) quake at 90° of epicentral distance

Additional slides

Investigations	Goals
Seismic activity determination	Formation of the Earth-Moon system
Constraints or determination of the stratification of the lunar interior	Evolution of the Moon
Constraints or determination of the thickness of the lunar crust and characterize its lateral variability.	Differentiation processes and evolution of the Moon
Existence, size, state, and composition of the lunar core	
Impact rate (NEOs)	

PAST, PRESENT AND FUTURE OF TERRESTRIAL PLANETS

From the Ranger missions of the 1960's to the future network missions of the Moon, seismometers have always been the core instruments of geophysical packages on the Moon. As a matter of fact, despite the non-spectacular appearance of the data output they provide they provide (compared to imagers or spectrometers), the analysis of their data provide unique insights to the understanding of the Moon as a planet, and is one of the sole way to investigate its deep interior, that is to say the existence of crust, core, or both, and the density distribution with depth. In this paper, we will review the main technical properties of the past missions instruments (Ranger, Apollo passive and active experiments) as well as their performances with respect to "consensus statement" science objectives, such as the impact flux and its internal structure. We will also summarize briefly their main achievements. Nowadays, after a long eclipse period, such geophysical investigations on the Moon witness a renewed interest from the scientific community, and several missions propose to pursue and complement the Apollo ALSEP legacy. In this paper, we will also provide a review of some incoming instrumental projects and of their expected performances, along the scientific objectives they foresee.



Sensor & Deployment Assembly

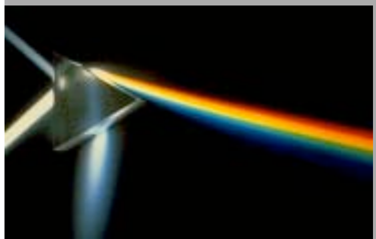
To deploy

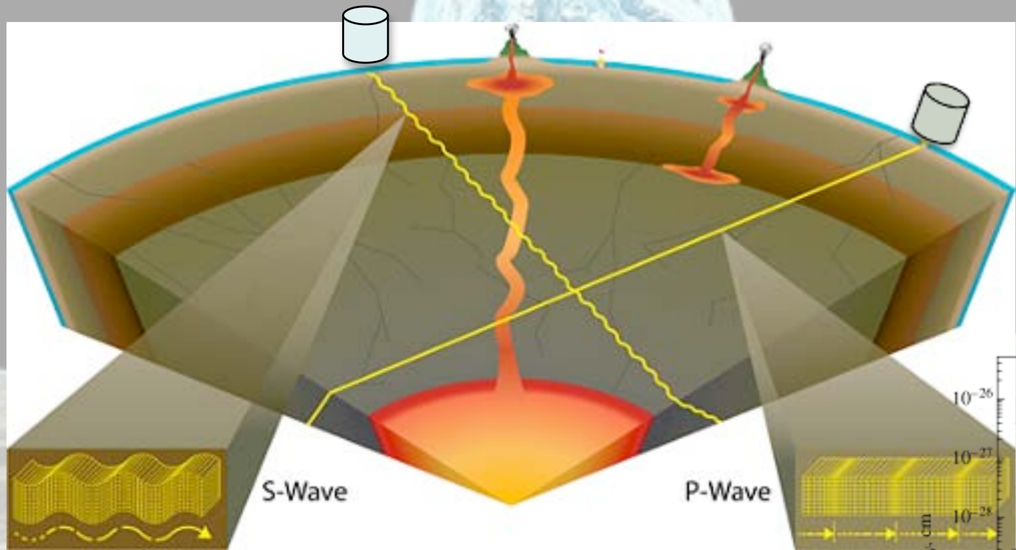
E-Box

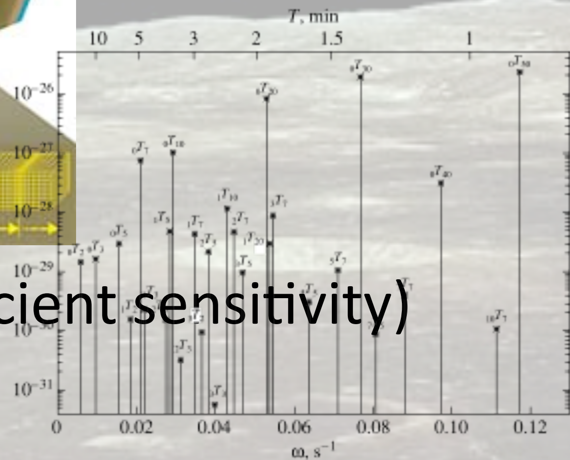
In "warm box"

Use of package avionics

- Seismic Waves emitted by a quake refract themselves as they encounter the layers interface (just like a prism)
- With enough events and nodes (but no always) , one can retrieve the propagation profiles.







- With a reduced node number (and a sufficient sensitivity) => study of eigenmodes